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DEVELOPMENT OF HIGH-EFFICIENCY SOLAR CELLS ON SILICON WEB

WESTINGHOUSE ELECTRIC CORP.

A. Rohatgi
D.L. Meier
R.B. Campbell
R.G. Seidensticker
P. Rai-Choudhury

Tasks

- **Perform Model Calculations to Design High Efficiency Web Cells**
- **Investigate the Influence of Twin Planes, Trace Impurities and Heat Treatment to improve Minority Carrier Lifetime in Web**
- **Develop and Optimize Advanced Design Features, Like Passivation, AR Coating and Back Surface Reflector**
- **Fabricate High Efficiency Web Cells With Efficiency Approaching 18%**

Calculated AM1 Performance of Standard and Low-Resistivity Web Cells With Base Diffusion Length as a Parameter

A. 4 Ohm-cm (3.5e15/cm^3) P-Type, 150 Microns Thick

Ln (Microns)	J_{oe} (A/cm^3)	J_{ob} (A/cm^3)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	Eff (%)	Eff' (%)
10	1.6e-12	32.1e-11	24.6	.471	.793	9.2	8.3
30	1.6e-12	9.5e-11	30.6	.508	.802	12.5	11.2
60	1.6e-12	5.3e-11	33.2	.525	.809	14.1	12.7
150	1.6e-12	2.0e-11	36.5	.551	.815	16.4	14.8
300	1.6e-12	1.1e-11	37.6	.566	.819	17.4	15.7

B. 0.2 Ohm-cm (1.0e17/cm^3) P-Type, 150 Microns Thick

Ln (Microns)	J_{oe} (A/cm^3)	J_{ob} (A/cm^3)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	Eff (%)	Eff' (%)
10	1.6e-12	7.5e-12	24.2	.563	.817	11.1	10.0
30	1.6e-12	2.5e-12	30.0	.589	.824	14.6	13.1
60	1.6e-12	1.2e-12	33.0	.601	.826	16.4	14.8
150	1.6e-12	0.6e-12	35.1	.609	.831	17.8	16.0
300	1.6e-12	0.5e-12	35.7	.611	.832	18.1	16.3

Note:

1. Calculations Were Made Using Martin Wolf's Program SPCOLAY.BAS
2. Calculated Values Do Not Account For Grid Shadowing, Light Reflection, Or Resistive Losses. In Order To Estimate These Effect, The Calculated Efficiency (Eff) Was Multiplied By 90% To Give A More Realistic Efficiency (Eff').
3. The Model Accounts For Variation In Doping Density In The Emitter And In The Back Region. For Both The n+p And p+p Regions The Junction Depth Was Taken To Be 0.3 Microns With A Surface Concentration Of 8.0e19/cm^3.
4. S_{front} = 10^4 cm/sec (AR On Bare Si); S_{back} = 10^6 cm/sec (Metal on Si)

Resistivity and Diffusion Length Requirements for 17.5%-Efficient Web Solar Cells

$W = 150\ \mu m$

$S_o p^+ = 500$ cm/sec

$N_{xj} = 3 \times 10^{17}\ cm^{-3}$

$S_o n^+ = 500$ cm/sec

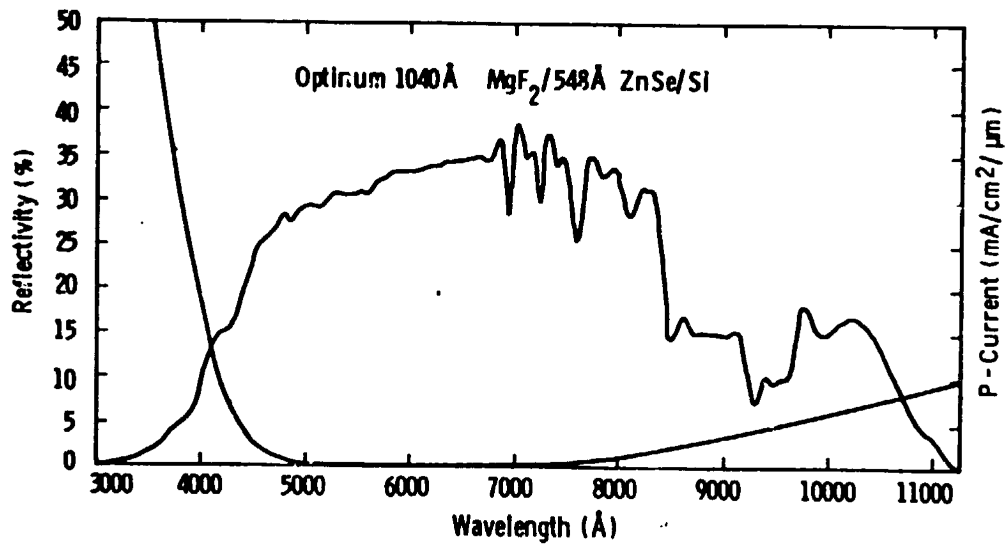
$N_s = 2 \times 10^{20}\ cm^{-3}$

$S_{p-p+} = 100$ cm/sec

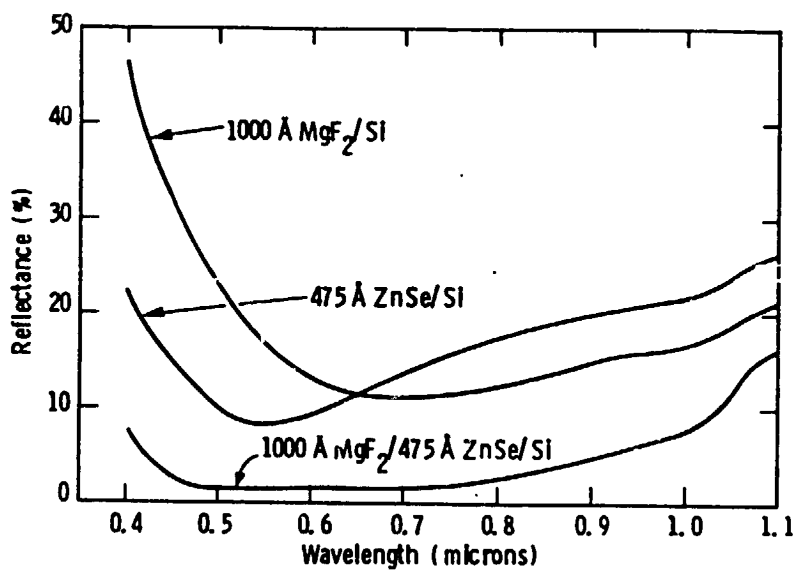
ρ Ω-cm	L μm	J_{sc} ma/cm²	V_{oc} Volts	η %
4.0	360	35	.589	17.0
4.0	467	35.2	.597	17.5
0.2	360	35.0	.643	18.8
0.2	125	33.2	.634	17.5

Solar-Cell Data on 4 Ohm-cm Web With and Without Oxide Passivation

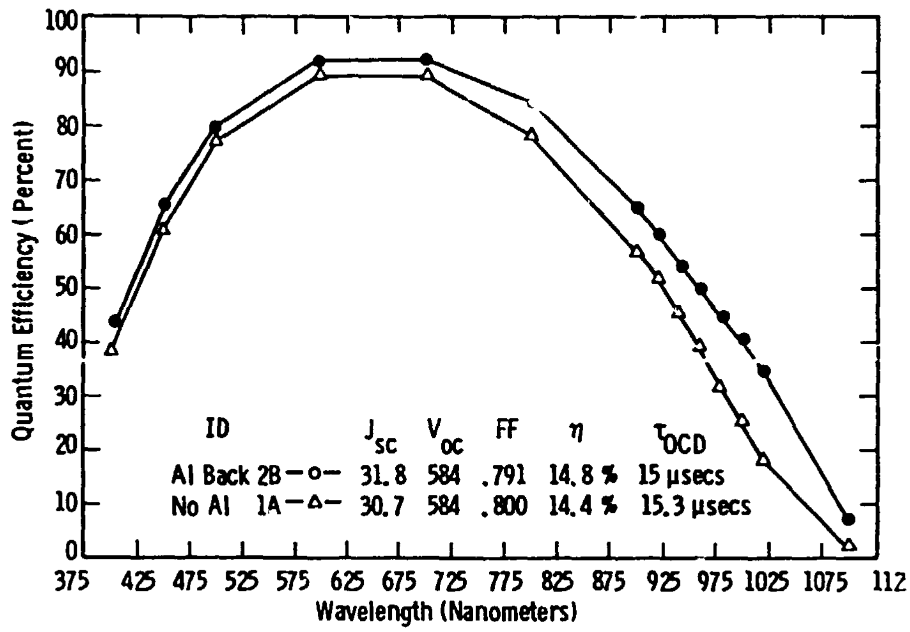
Cell ID	Short-Circuit Current J_{sc} (mA/cm²)	Open-Circuit Voltage V_{oc} Volts	Fill Factor	Cell Efficiency (%)
		Without Passivation		
W6	32.7	0.575	0.732	14.7
W7	33.1	0.577	0.784	15.0
		With Oxide Passivation		
W1	34.6	0.584	0.784	15.9
W2	34.5	0.586	0.794	15.8



Experimentally Determined Reflectance Curves for
(a) 1000 A MgF_2/Si; (b) 475 A ZnSe/Si, and
(c) 1000 A MgF_2/475 A ZnSe/Si



Effect of Aluminum Back-Surface Reflector on Web Cell Performance



Baseline Web Solar Cells on 0.37 Ohm-cm Web (Crystal No. 4-275) Without AR Coating, Back-Surface Reflector, and Oxide Passivation

Cell ID	J_{sc} mA/cm^2	V_{oc} mV	FF	Efficiency %
6-1-2	21.3	579	.790	9.7
6-2-6	21.6	575	.803	10.0
6-3-6	22.1	574	778	9.9

Hiefy 20, Qual.

Crystal #6

AM1, 100 mW/cm^2 Illumination

Low-Resistivity (0.37 Ohm-cm) High-Efficiency Web Solar Cells With Surface Passivation, BSR and Evaporated Double-Layer AR Coating

Cell ID	Area cm^2	J_{sc} mA/cm^2	V_{oc} mV	FF	η %
1-1	1.0	35.2	600	0.800	16.9
1-2	1.0	35.2	600	0.800	16.9
1-3	1.0	35.0	598	0.802	16.8
1-4	1.0	34.9	598	0.800	16.7
1-5	1.0	35.2	596	0.793	16.7
1-6	1.0	35.1	596	0.792	16.6

*Run # Hiefy 20, Web #1
*AM1, 100 mW/cm^2 illumination

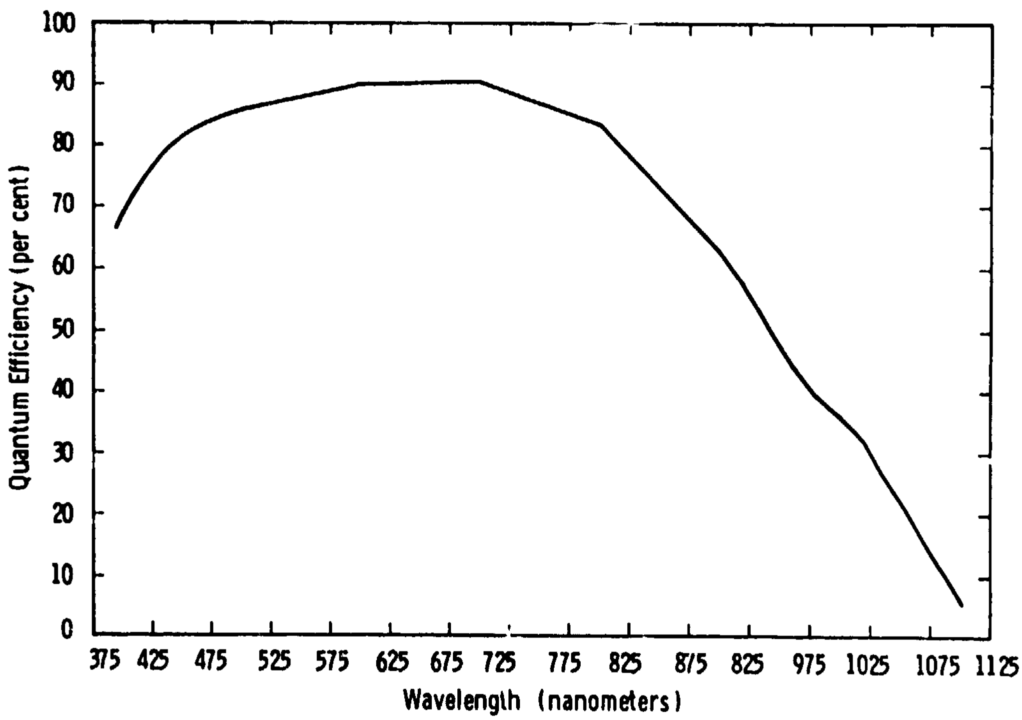


Fig. 6 — Internal quantum efficiency versus wavelength plot for 16.9% efficient web solar cell with oxide passivation, evaporated double-layer AR coating and aluminum back-surface reflector (hiefy 20, web 1-4)

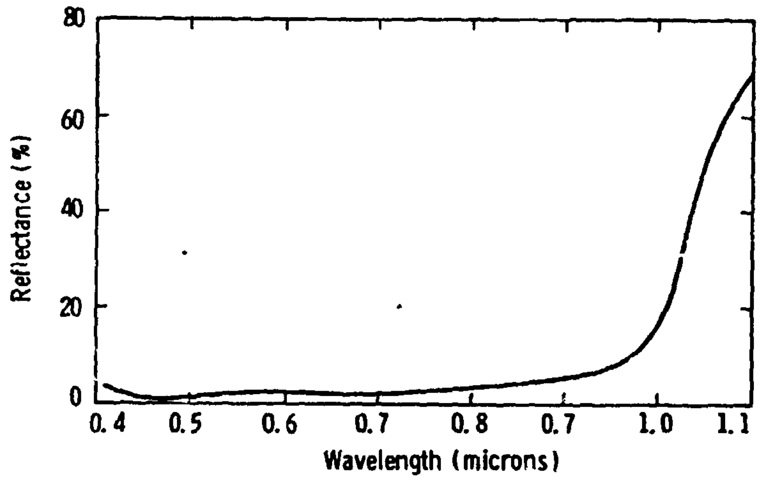


Fig. 8 – Reflectance as a function of wavelength for 16.9% efficient wet cell with oxide passivation, evaporated ZnSe+MgF_2 double-layer antireflective coating, and aluminum back-surface reflector

Diffusion Length in Low-Resistivity Web Crystal No. 4-275, Which Gave 16.9%-Efficient Web Cells

As Grown Crystal - 30 μm - SPV

Processed Cell - 90 μm - SPV

150 μm - OCVD

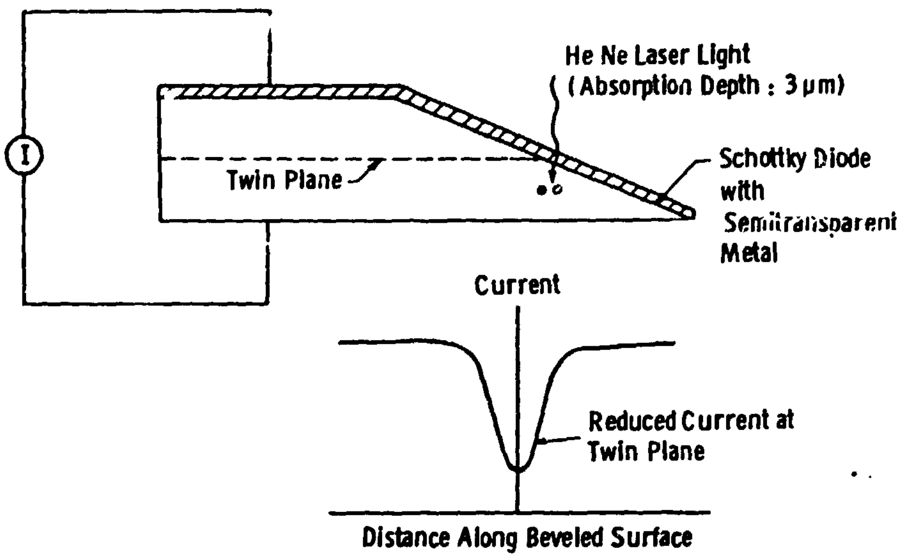


Fig. 6—Sensing the electrical activity of the twin plane with light-beam-induced current (LBIC)

Examples of Large-Area Web Cells With Ratio of Twin Plane Depth to Minority Carrier Diffusion Length as a Parameter

Twin Plane Depth / Diffusion Length	Diffusion Length μm	Twin Plane Depth μm	Cell Thickness μm	J_{sc} mA/cm²	V_{oc} V	FF	Eff %
0.33	78	26	153	31.4	0.591	0.81	15.1
0.50	116	58	164	31.6	0.591	0.81	15.3
0.72	86	62	133	30.8	0.591	0.81	14.9
0.84	61	51	130	30.9	0.590	0.80	14.6
1.14	50	57	132	30.8	0.589	0.80	14.5
1.52	65	99	165	31.1	0.589	0.81	14.9

Notes: 1. Cell Size is 9.8 × 2.5 cm, and Base is Boron-Doped to 4 Ohm-cm.
2. Cell Data Acquired Using AM1 Spectrum, 100 mW/cm² Intensity at Room Temperature.
3. Diffusion Length Measured by Surface Photovoltage Technique.

Observations: For Cells Where Twin Plan Depth << Diffusion Length, the Carrier Recombinationat the Twin Planes is Not Significant Compared to Recombination in the Bulk.

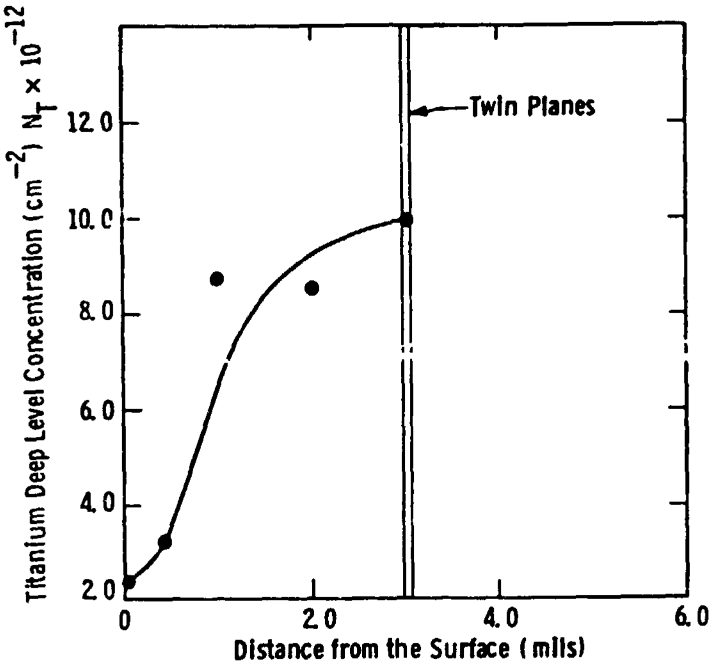
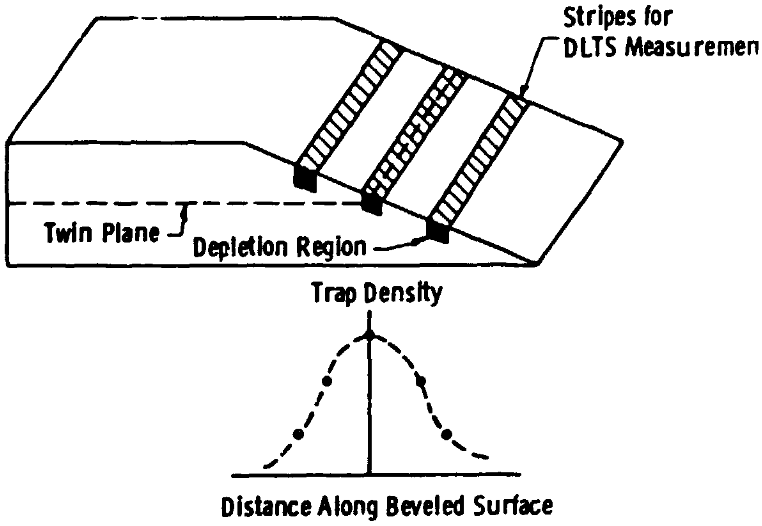


Fig. 5—DLTS study of the interaction between grown-in Titanium impurity and the twin planes in dendritic web silicon



- Use a Grown-In Impurity (Ti, V) as an Internal Tracer
- Observe Trap Density as a Function of Distance from Twin Plane, Both As-Grown and After Processing (Including Gettering)
- Compare Web Having High Diffusion Length with Web Having Low Diffusion Length (As Determined by SPV) Using this Technique

Fig. 1—Detecting and identifying impurities piled up at the twin plane by DLTS

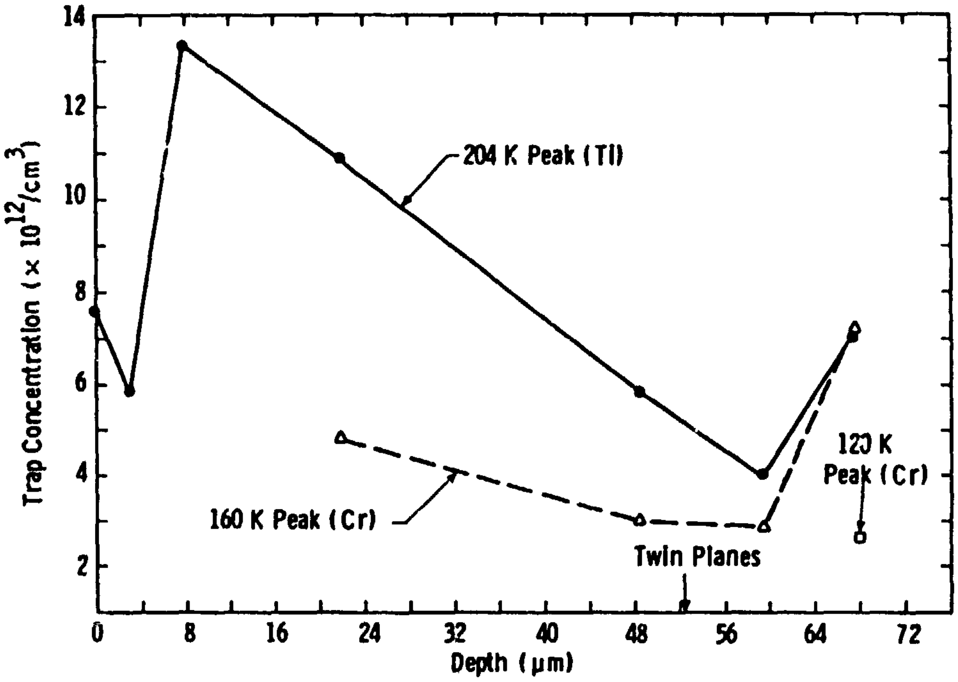


Fig. 3—Depth profile of traps detected by DLTS for Ti-doped dendritic web silicon crystal J167-1.1, as-grown. (Sample #T4 from Run TP-4). Web crystal is 4 ohm-cm, p-type